

Discovery of Scalar Mixed With SM Higgs Via Diboson Excess at the LHC

Sibo Zheng*

Department of Physics, Chongqing University, Chongqing 401331, P. R. China

The prospect for the discovery of scalar weakly mixed with the SM Higgs is studied through the diboson signal excess at the Large Hadron Collider. Such scalar usually exists in scalar singlet extended SM. For illustration to the broad application of our scenario, the next-to-minimal supersymmetric model and a real scalar singlet extended SM are studied as two interesting examples.

I. INTRODUCTION

The scalar with mass around 125 GeV discovered at the Large Hadron Collider (LHC) [1] establishes the Standard Model (SM) as the effective field theory below the electroweak scale. Unfortunately, SM cannot be considered as a self-consistent theory. One reason is that it stands at the critical point to guarantee the electroweak vacuum stability [2] for the observed Higgs mass, which is further challenged by large quantum fluctuations [3] in the early Universe. Another more obvious reason is that it doesn't provide reasonable candidate of dark matter, the relic density of which has been measured in high precision by the Plank and WIMP 9-year data [4].

Among new physics models proposed to address the problems above, there is usually scalar H of the same spin, parity, and quantum numbers as the SM-like Higgs. Without no doubt they may mix with each other in various ways. The magnitude of this mixing effect has been bounded above [5] in the light of precise measurement on the SM Higgs couplings performed at the LHC.

Motived by the recent ATLAS experiment about the SM diboson excess [6], we study the prospect for the discovery of scalar which weakly mixes with the SM-like Higgs through the SM diboson excesses at the LHC. The main reason for searching such scalar decaying into diboson channels is based on the fact that through the mixing effect H couples to the SM fermions and bosons similarly to the SM-like Higgs, except that there is an universal scaling factor smaller than unity. As a result, diboson decays $V_i V_i$ with $V_i = \{W, Z\}$ dominate others in the mass range $m_H \geq 200$ GeV.

The paper is organizied as follows. In Section II and III we address the production cross section for $\sigma(pp \rightarrow H \rightarrow VV)$ at the 8 TeV and 14 TeV LHC for the mass range 100 GeV

* sibozheng.zju@gmail.com

$\leq m_H \leq 1000$ GeV in model-independent way. This is achieved in terms of the measured production cross section [7, 8] and decay [9] for the SM-like Higgs. While the background for SM diboson signal is reconstructed by using the data of 20.3 fb^{-1} at the 8 TeV LHC ¹. Given different integrated luminosity the mass ranges for 5σ discovery at 8 TeV LHC will be explicitly work out for small, moderate and large mixing effect, respectively.

Section IV is devoted to the application to new physics models. We show that in two interesting examples, i.e., the next-to-minimal supersymmetric model (NMSSM) and the scalar singlet extension of SM, some part of the parameter space is exactly covered by the phenomenological study of Sec. II and III. Finally, we conclude in Sec.V.

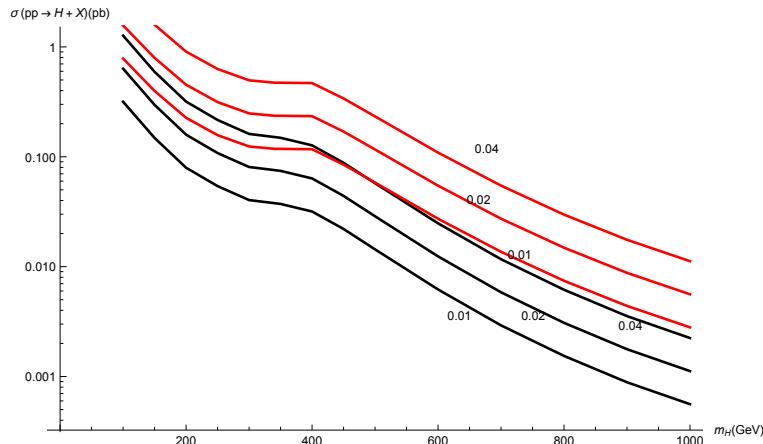


FIG. 1. Production cross section for scalar H at the LHC with $\sqrt{s} = 8$ TeV (black color) and 14 TeV (red color) respectively for three representative values $\sin^2 \alpha = \{0.01, 0.02, 0.04\}$.

II. PRODUCTION CROSS SECTION AT THE LHC

When there is a new scalar state H which has the same spin, parity and quantum numbers as the SM-like Higgs h they probably mix with each other. In this section we discuss the production and decay of such scalar in the case of weak mixing as allowed by the precise measurement on the SM Higgs couplings. We focus on the discovery of this scalar through the SM diboson excess at the LHC, which will shed light on the WW and ZZ excesses at $\sim 3\sigma$ level reported by the ATLAS collaboration.

Let us define the mass squared matrix for state vector (H, h) in the decoupling limit as,

$$\begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} \quad (1)$$

¹ Similar analysis can be directly performed once the background for SM diboson signal at the 14 TeV LHC is measured.

If the mixing between the SM Higgs h and H scalar can be ignored, in the same spirit of what occurs in scalar dark matter model, there is no chance for the discovery of H at the LHC. Conversely, if the mixing is significant, H would have been excluded by the LHC searches such as dijet, diphoton and four lepton signals, etc. In other words, there is room only for a small mixing effect, which can be realized by introducing a small off-diagonal element Δm^2 into the mass squared matrix in Eq.(1),

$$\begin{pmatrix} m_H^2 & \Delta m^2 \\ \Delta m^2 & m_h^2 \end{pmatrix} \quad (2)$$

In the next section such realization will be shown to cover much of parameter space of new physics models. Because of small Δm^2 the mass eigenvalues will be slightly modified as,

$$\begin{aligned} m_H^2 &\rightarrow m_H^2 + \frac{(\Delta m^2)^2}{m_H^2 - m_h^2}, \\ m_h^2 &\rightarrow m_h^2 - \frac{(\Delta m^2)^2}{m_H^2 - m_h^2}. \end{aligned} \quad (3)$$

Remarkably, the strengths of SM-like couplings $h - X_i - X_i$, where X_i refers to the SM vector bosons and fermions, are reduced in compared with the SM expectation, and conversely those of couplings $H - X_i - X_i$ are enhanced. Note that their tree-level values are zero in the decoupling limit. In the presence of the mixing effect these couplings are given by in normalized to what the SM expects,

$$\frac{g_{hXX}^2}{g_{h_{\text{SM}}XX}^2} = \cos^2 \alpha, \quad \frac{g_{HXX}^2}{g_{h_{\text{SM}}XX}^2} = \sin^2 \alpha, \quad (4)$$

where

$$\tan(2\alpha) = \frac{2\Delta m^2}{m_H^2 - m_h^2}. \quad (5)$$

The present LHC experiments on the precise measurement of SM-like Higgs coupling leads to an upper bound on the small quantity $\sin^2 \alpha \leq 0.04$ [5].

The production cross section $\sigma(pp \rightarrow H)$ can be obtained through that of the SM-like Higgs,

$$\sigma(pp \rightarrow H) = \tan^2 \alpha \times \sigma(pp \rightarrow h_{\text{SM}}) \quad (6)$$

This is true when H couples to the SM fermions and vector bosons similar to the SM-like Higgs expect an universal scaling factor $\sin \alpha$. The main contribution to $\sigma(pp \rightarrow H)$ arises from the gluon fusion and vector boson fusion processes. Adopt m_h as a free parameter instead of 125 GeV, Fig.1 shows $\sigma(pp \rightarrow H)$ at the LHC with the energy of mass center $\sqrt{s} = \{8, 14\}$ TeV, respectively. In Eq.(6) we have used $\sigma(pp \rightarrow h_{\text{SM}})$ which has been measured in terms of the reported data in [7, 8]. We have chosen three representative values $\sin^2 \alpha = \{0.01, 0.02, 0.04\}$ for comparison.

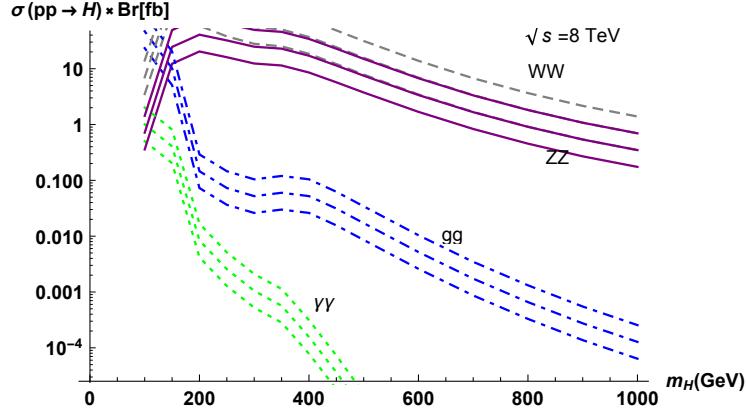


FIG. 2. The production cross sections for SM diboson at the LHC with $\sqrt{s} = 8$ TeV. The three lines in the same color corresponds to $\sin^2 \alpha = \{0.04, 0.02, 0.01\}$ from top to bottom, respectively.

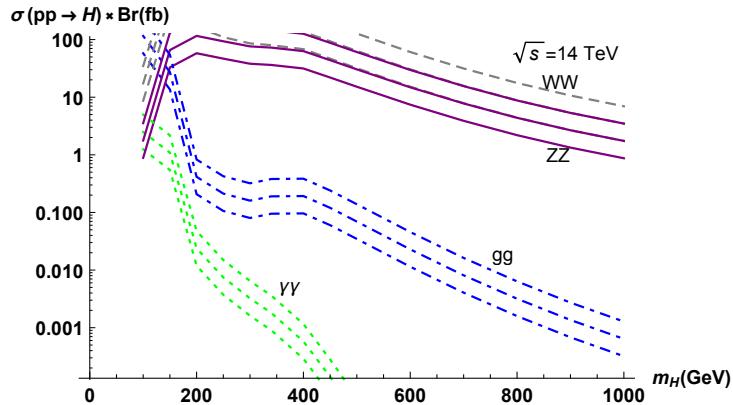


FIG. 3. Same as Fig.2 but with $\sqrt{s} = 14$ TeV instead.

The property among the couplings $H - X - X$ may be violated in some specific situation, e.g., in the parameter space of minimal supersymmetric SM model with $\tan \beta \neq 1$. As in the large $\tan \beta$ -region the b-quark fusion process will dominate the production cross section for H instead of gluon fusion [10], as a result of enhanced $H - b - b$ and suppressed $H - t - t$ couplings.

Since the mixing effect is rather small, the branching ratio $\text{Br}(H \rightarrow V_i V_i)$ is mildly dependent on the mixing effect through the possible decay $H \rightarrow hh$. Take the approximation in which this channel is ignored, we show in Fig.2 and Fig.3 the production cross sections of SM dibosons through the intermediate scalar H . We have not shown the bi-quark and bi-lepton channels, as they are so tiny in compared with the WW and ZZ channels. We refer the reader to HEDCAY [9] for more details about the branching ratios for each H decay channel. See also [8].

Among diboson decay channels, $H \rightarrow gg$ and $H \rightarrow \gamma\gamma$ are bounded by the LHC Run I

searches on dijet [11] and $\gamma\gamma$ [12] signal, respectively,

$$\begin{aligned}\sigma(pp \rightarrow H) \times \text{Br}(H \rightarrow gg) &\leq 200 \text{ fb}, \\ \sigma(pp \rightarrow H) \times \text{Br}(H \rightarrow \gamma\gamma) &\leq 0.5 \text{ fb}.\end{aligned}\quad (7)$$

In the light of Fig.2, we find that H with mass below ~ 200 GeV has been excluded. In what follows, we mainly focus on the range $300 \text{ GeV} \leq m_H \leq 1000 \text{ GeV}$.

Very recently, the ATLAS collaboration reported both WW and ZZ excesses at 3σ level [6] at the 8 TeV LHC. Fig.2 clearly shows that $\sigma(pp \rightarrow H)$ is far beneath 1 fb for $m_H \sim 2$ TeV, therefore scalar H in our scenario cannot serve as the origin of observed excess. If this excess is further verified at the Run II of LHC, it will imply that for scalar explanation its couplings to the SM fermions and bosons are rather different from those in our scenario.

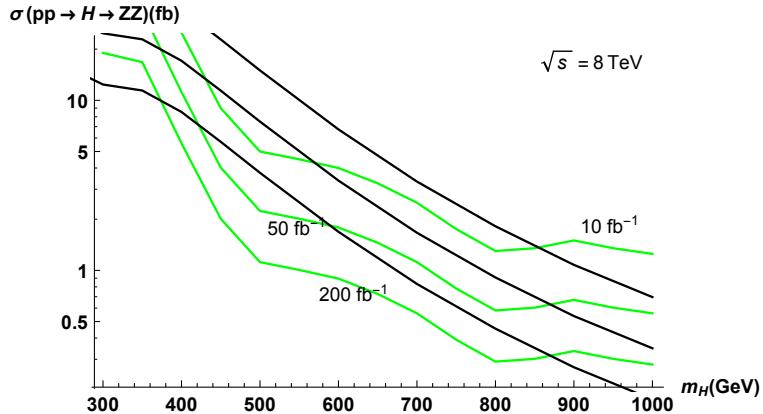


FIG. 4. The contours for 5σ discovery through ZZ decay at the 8 TeV LHC for different integrated luminosities $\mathcal{L} = \{10, 50, 200\} \text{ fb}^{-1}$.

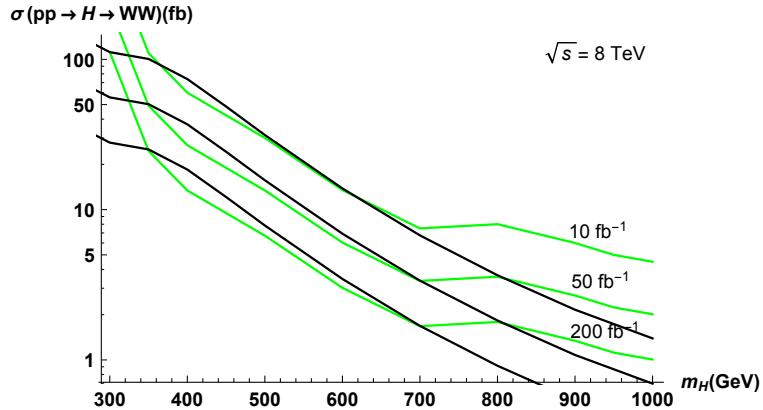


FIG. 5. Same as Fig.4 but WW decay instead.

III. PROSPECT FOR DISCOVERY

In order to discuss the prospect for 5σ discovery for H , the SM background for diboson production at the LHC should be reconstructed. In terms of the data of 20.3 fb^{-1} collected by the LHC Run I data for ZZ production [13] and WW production [14], the production cross sections $\sigma_{\text{SM}}(pp \rightarrow ZZ)$ and $\sigma_{\text{SM}}(pp \rightarrow WW)$ can be reproduced accordingly. See [15, 16] for other diboson channels.

By combining Fig.2 we show in Fig.4 and Fig.5 the mass ranges for the 5σ discovery given different integrated luminosities $\mathcal{L} = \{10, 50, 200\} \text{ fb}^{-1}$ at the 8 TeV LHC. These figures clearly indicate that

- for the maximal mixing effect $\sin^2 \alpha \simeq 0.04$, m_H below 850 (700) GeV can be excluded with data of 20 fb^{-1} through the ZZ (WW) decay.
- for moderate mixing $0.02 \leq \sin^2 \alpha < 0.04$, m_H below 1 TeV can be fully detected with data of 200 fb^{-1} through the ZZ decay.
- for small mixing effect $\sin^2 \alpha < 0.01$, there is no chance for the discovery in the whole mass range $100 \text{ GeV} \leq m_H \leq 1000 \text{ GeV}$ except that we have significantly larger integrated luminosity.

The analysis can be performed for the 14 TeV LHC similarly. Once $\sigma_{\text{SM}}(pp \rightarrow ZZ)$ and $\sigma_{\text{SM}}(pp \rightarrow WW)$ are measured at the 14 TeV LHC, it can be completed in terms of Fig.3.

IV. EXAMPLES

In this section we apply the phenomenological insights in the previous two sections to two interesting example, i.e., NMSSM and a real scalar singlet extended SM. We show that either the NMSSM with Peccei-Quinn (PQ) symmetry (IV.A), or the scalar singlet extension of SM with only quartic coupling between singlet and Higgs (IV.B), is covered by our scenario in some part of parameter space. These examples indicate that scalar weakly mixed with the SM-like Higgs is the main signal at the LHC.

A. NMSSM with PQ symmetry

The first example is the NMSSM with an approximate $U(1)$ PQ symmetry. The parameter space of such model is composed of only five model parameters $\{\lambda, \kappa, A_\lambda, \tan \beta, m_s^2\}$ ², in

² We follow the conventions and notation in [17]. See also [18].

which λ and κ appear in the Lagrangian as $\mathcal{L} \sim \lambda S H_\mu H_d + \frac{\kappa}{3} S^3 + \dots$, and A_λ refers to the A-term. Under the decomposition,

$$\begin{aligned} H_u^0 &= \frac{1}{\sqrt{2}}(h_1 + i\pi_1), \\ H_d^0 &= \frac{1}{\sqrt{2}}(h_2 + i\pi_2), \\ S &= \frac{1}{\sqrt{2}}(s + i\pi_s), \end{aligned}$$

we obtain the 3×3 squared mass matrix of CP-even neutral scalars

$$\mathcal{M}^2 = \begin{pmatrix} \frac{A_\lambda^2}{1+x} + (M_Z^2 - \lambda^2 v^2) \sin^2 2\beta + \dots & -\frac{1}{2}(m_Z^2 - \lambda^2 v^2) \sin 4\beta + \dots & -A_\lambda \lambda v \cos 2\beta + \dots \\ \times & M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \dots & -A_\lambda \lambda v \sin 2\beta \frac{x}{1+x} + \dots \\ \times & \times & \lambda^2 v^2(1+x) + \dots \end{pmatrix} \quad (8)$$

in the basis (H, h, s) , where

$$\begin{aligned} H &= \cos \beta h_2 - \sin \beta h_1, \\ h &= \cos \beta h_1 + \sin \beta h_2, \end{aligned}$$

and $x \equiv m_S^2/(\lambda v)^2$, with $v = 174$ GeV. Terms ignored in Eq.(8) vanish in the PQ limit, $\kappa \rightarrow 0$.

Let us show which scalar is the SM-like Higgs and which one plays the role of H in Sec.II. Impose the limit $\lambda \rightarrow 0$ and $\kappa \rightarrow 0$, all three scalars decouple and the mass for h reads as $\mathcal{M}_{22}^2 \simeq M_Z^2 \cos^2 2\beta$, which reproduces the well-known result in the case of MSSM. So h serves as the SM-like Higgs, H and S mix with h through the mixing terms \mathcal{M}_{12}^2 and \mathcal{M}_{23}^2 in Eq.(8), and the magnitude of these mixing effects is determined by λ , κ , etc. With the PQ symmetry the requirement from the decoupling limit

$$\mathcal{M}_{12}^2 = 0, \quad \mathcal{M}_{23}^2 = 0 \quad (9)$$

can be satisfied in various situations.

- Case I: $\sin 4\beta = 0$, and $\lambda = 0$. In this case the NMSSM is actually not well defined.
- Case II: $\sin 4\beta = 0$, and $\sin 2\beta = 0$. In this case effective μ term as given by $\mu_{\text{eff}} = A_\lambda \sin(2\beta)/2(1+x)$ vanishes.
- Case III: $\sin 4\beta = 0$, and $x = 0$. This case is reasonable for small soft mass m_s , which is true in some specific model buildings, e.g., conventional gauge mediation. The decoupling limit in this case correspond to $\kappa = 0$, $x = 0$ and $\beta_c = \pi/4$.

Introduce a small deviation $\beta = \beta_c + \delta$, where $|\delta| \ll 1$, it gives rise to small mixing between h and H through non-zero \mathcal{M}_{12}^2 , in which the mass matrix in Eq.(8) is reduced to

$$\mathcal{M}^2 \simeq \begin{pmatrix} A_\lambda^2 & 2\delta(m_Z^2 - \lambda^2 v^2) & 2\delta A_\lambda \lambda v \\ \times & M_Z^2 & 0 \\ \times & \times & \lambda^2 v^2 \end{pmatrix} \quad (10)$$

From Eq.(10) we obtain the mass eigenvalues,

$$\begin{aligned} m_H^2 &\simeq A_\lambda^2 + \mathcal{O}(\delta^4), \\ m_s^2 &\simeq \lambda^2 v^2 + \mathcal{O}(\delta^4), \\ m_h^2 &= m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2} \log\left(\frac{m_t^2}{m_{\tilde{t}}^2}\right). \end{aligned} \quad (11)$$

Here $m_{\tilde{t}}$ denotes the stop scalar mass. The non-zero matrix element \mathcal{M}_{13}^2 contributes to order δ^4 correction to masses m_H^2 and m_s^2 . For completeness, we outline mass eigenvalues for CP-odd and charged scalars,

$$\begin{aligned} m_{A_1}^2 &\simeq m_H^2 + m_s^2, \\ m_{H^\pm}^2 &\simeq m_W^2 + m_H^2 - m_s^2. \end{aligned} \quad (12)$$

For the PQ Goldstone mode $m_{A_2} \sim 0$, and $\mu_{\text{eff}} = A_\lambda/2$.

Through \mathcal{M}_{13}^2 scalar s indirectly mixes with h through mixing with scalar H . Therefore, the mixing effect between h and s can be ignored in compared with that of h and H . This implies that NMSSM with parameter choices in the case III, is effectively covered by the new physics model discussed in Sec. II and III. In order to explain the observed Higgs mass $m_h \simeq 125.5$ GeV [1] $m_{\tilde{t}} > 1$ TeV is required similar to the MSSM. Take these points into account scalar H might be the main signal at the LHC.

B. SM With Scalar Singlet

Consider the scalar singlet extension of SM with a real scalar s . As a SM singlet, s can directly couple to the SM Higgs. We employ a Z_2 parity ³ under which s is odd for simplifying the potential V ,

$$V(s, H) = \frac{\mu^2}{2} H^2 + \frac{\lambda}{2} H^4 + \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{2} s^4 + \frac{\kappa}{2} s^2 |H|^2. \quad (13)$$

For simplicity, we assume that all dimensionless couplings in Eq.(13) are positive.

³ It was firstly employed to keep s stable, then used to construct the minimal dark matter model [19]. Note that in this case no mixing between s and h occurs.

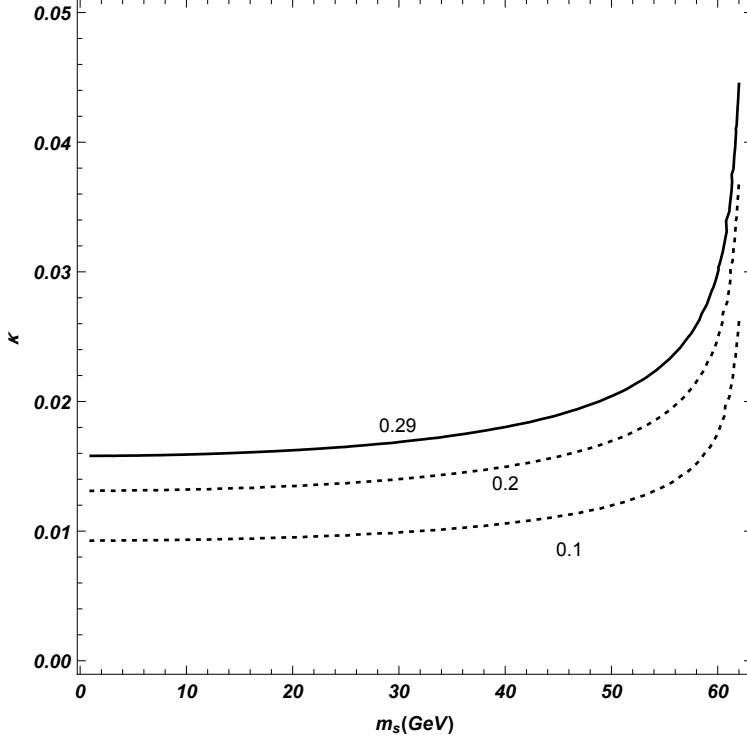


FIG. 6. Contour of invisible branching ratio $h \rightarrow ss$ in the parameter space of $m_s - \kappa$. The solid line corresponds to the present bound $\text{Br}_{\text{inv}} \leq 0.29$.

Whether the mixing between s and h happens depends on the signs of μ_s^2 , which corresponds to different vacuum structures. Write the vacuum expectation values (vevs) as $\langle s \rangle = v_s$ and $\langle H \rangle = v$, they must satisfy,

$$\begin{aligned} \mu_s^2 + \kappa v^2 + 2\lambda_s v_s^2 &= 0, \\ \mu^2 + \kappa v_s^2 + 2\lambda v^2 &= 0. \end{aligned} \quad (14)$$

Expand the fields as $s = v_s + s'$ and $H = (v + h/\sqrt{2}, 0)$, we obtain the mass squared matrix for the basis $(h, s)^T$,

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda v^2 & \frac{\kappa}{\sqrt{2}} v v_s \\ \times & 4\lambda_s v_s^2 \end{pmatrix} \quad (15)$$

Eq.(15) and Eq.(14) imply that mixing effect occurs only when the signs of μ_s^2 and μ^2 are both negative. If so, the magnitude of mixing effect between h and s is controlled by parameter κ .

For small κ the LHC phenomenology of this model is totally covered by the previous discussions in Sec. II and III. If λ_s is also small, s can be further constrained by the decay $h \rightarrow ss$ for $m_s < m_h/2$ [20]. Fig.6 shows the value of κ consistent with the present measurement on the Higgs invisible decay branching ratio $\text{Br}_{\text{inv}} \leq 0.29$ [21] .

V. CONCLUSION

In this paper we have considered the prospect for the discovery of SM singlet which weakly mixes with the SM Higgs. Take into account the allowed magnitude of the mixing effect by the precise measurement on the Higgs couplings, we have shown the mass ranges for 5σ discovery at the 8 TeV LHC for different integrated luminosities. This scenario can be applied to many interesting new physics models. For illustration, we explicitly consider the NMSSM and scalar singlet extension of SM, in which we show that our scenario covers much of the parameter space for each case.

ACKNOWLEDGMENTS

This work is supported in part by the National Natural Science Foundation of China under grant No.11247031 and 11405015.

- [1] G. Aad *et al.* [ATLAS Collaboration], “Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$ with the ATLAS detector at the LHC,” *Phys. Lett. B* **710**, 49 (2012), arXiv:1202.1408 [hep-ex];
S. Chatrchyan *et al.* [CMS Collaboration], “Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ ” *Phys. Lett. B* **710**, 26 (2012), arXiv:1202.1488 [hep-ex].
- [2] D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, “Investigating the near-criticality of the Higgs boson,” *JHEP* **1312**, 089 (2013), arXiv:1307.3536 [hep-ph].
- [3] A. Kobakhidze and A. Spencer-Smith, “Electroweak Vacuum (In)Stability in an Inflationary Universe,” *Phys. Lett. B* **722**, 130 (2013), arXiv:1301.2846 [hep-ph];
A. Hook, J. Kearney, B. Shakya and K. M. Zurek, “Probable or Improbable Universe? Correlating Electroweak Vacuum Instability with the Scale of Inflation,” *JHEP* **1501**, 061 (2015), arXiv:1404.5953 [hep-ph];
J. R. Espinosa, G. F. Giudice, E. Morgante, A. Riotto, L. Senatore, A. Strumia and N. Tetradis, “The cosmological Higgstory of the vacuum instability,” arXiv:1505.04825 [hep-ph].
- [4] Planck Collaboration, “Planck 2013 results. XVI. Cosmological parameters,” *Astron. Astrophys.* **571**, A16 (2014), arXiv:1303.5076 [astro-ph.CO].
- [5] See, e.g., A. Falkowski, F. Riva and A. Urbano, “Higgs at last,” *JHEP* **1311**, 111 (2013). arXiv:1303.1812 [hep-ph].
- [6] G. Aad *et al.* [ATLAS Collaboration], “Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS detector,” arXiv:1506.00962 [hep-ex].
- [7] <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV>.
- [8] S. Dittmaier *et al.* [LHC Higgs Cross Section Working Group Collaboration], “Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables,” arXiv:1101.0593 [hep-ph].

- [9] A. Djouadi, J. Kalinowski and M. Spira, “HDECAY: A Program for Higgs boson decays in the standard model and its supersymmetric extension,” *Comput. Phys. Commun.* **108**, 56 (1998), [hep-ph/9704448].
- [10] D. A. Dicus and S. Willenbrock, “Higgs Boson Production from Heavy Quark Fusion,” *Phys. Rev. D* **39**, 751 (1989);
A. Arbey, M. Battaglia and F. Mahmoudi, “Supersymmetric Heavy Higgs Bosons at the LHC,” *Phys. Rev. D* **88**, no. 1, 015007 (2013), arXiv:1303.7450 [hep-ph].
- [11] G. Aad *et al.* [ATLAS Collaboration], “Search for new phenomena in the dijet mass distribution using $p - p$ collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *Phys. Rev. D* **91**, no. 5, 052007 (2015), arXiv:1407.1376 [hep-ex];
V. Khachatryan *et al.* [CMS Collaboration], “Search for resonances and quantum black holes using dijet mass spectra in proton-proton collisions at $\sqrt{s} = 8$ TeV,” *Phys. Rev. D* **91**, no. 5, 052009 (2015), arXiv:1501.04198 [hep-ex].
- [12] G. Aad *et al.* [ATLAS Collaboration], “Search for high-mass diphoton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” arXiv:1504.05511 [hep-ex].
- [13] G. Aad *et al.* [ATLAS Collaboration], “Search for resonant diboson production in the $\ell\ell q\bar{q}$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *Eur. Phys. J. C* **75**, no. 2, 69 (2015), arXiv:1409.6190 [hep-ex].
- [14] G. Aad *et al.* [ATLAS Collaboration], “Search for production of WW/WZ resonances decaying to a lepton, neutrino and jets in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *Eur. Phys. J. C* **75**, no. 5, 209 (2015), arXiv:1503.04677 [hep-ex].
- [15] V. Khachatryan *et al.* [CMS Collaboration], “Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at $\sqrt{s} = 8$ TeV,” *JHEP* **1408**, 174 (2014), arXiv:1405.3447 [hep-ex].
- [16] V. Khachatryan *et al.* [CMS Collaboration], “Search for massive resonances in dijet systems containing jets tagged as W or Z boson decays in pp collisions at $\sqrt{s} = 8$ TeV,” *JHEP* **1408**, 173 (2014), arXiv:1405.1994 [hep-ex].
- [17] R. Barbieri, L. J. Hall, A. Y. Papaioannou, D. Pappadopulo and V. S. Rychkov, “An Alternative NMSSM phenomenology with manifest perturbative unification,” *JHEP* **0803**, 005 (2008), arXiv:0712.2903 [hep-ph].
- [18] S. Zheng, “Perturbative λ -Supersymmetry and Small κ -Phenomenology,” *Eur. Phys. J. C* **75**, no. 5, 195 (2015), arXiv:1405.6907 [hep-ph].
- [19] V. Silveira and A. Zee, “Scalar Phantoms,” *Phys. Lett. B* **161**, 136 (1985) ;
J. McDonald, “Gauge singlet scalars as cold dark matter,” *Phys. Rev. D* **50**, 3637 (1994), [hep-ph/0702143];
C. Burgess, M. Pospelov, and T. ter Veldhuis, “The Minimal model of nonbaryonic dark matter: A Singlet scalar,” *Nucl. Phys. B* **619**, 709 (2001), [hep-ph/0011335].
- [20] D. O’Connell, M. J. Ramsey-Musolf and M. B. Wise, “Minimal Extension of the Standard Model Scalar Sector,” *Phys. Rev. D* **75**, 037701 (2007), [hep-ph/0611014];
V. Barger, P. Langacker, M. McCaskey, M. J. Ramsey-Musolf and G. Shaughnessy, “LHC Phenomenology of an Extended Standard Model with a Real Scalar Singlet,” *Phys. Rev. D* **77**, 035005 (2008), arXiv:0706.4311 [hep-ph].
- [21] G. Aad *et al.* [ATLAS Collaboration], “Search for an Invisibly Decaying Higgs Boson Produced via Vector Boson Fusion in pp Collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC,” ATLAS-CONF-2015-004.